NEW VIEWS ON THE PROBLEM OF CP VIOLATION [a]

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ABSTRACT

After briefly recollecting basic features of the good-old way of detecting CP violation by comparing ν_e and $\bar{\nu}_e$ appearance measurement in long-baseline (LBL) neutrino oscillation experiments, I discuss two new ways of exploring leptonic CP violation. First, I discuss the reactor-LBL method in which reactor measurement of θ_{13} is combined with ν_e (no $\bar{\nu}_e$) appearance measurement in LBL. Assuming $\sim 10^3$ GW$_{th}$·ton·year operation of a reactor experiment, CP sensitivity at 90 % CL is shown to exists in $\sin^2 2\theta_{13} > 0.03$ (0.04) with 2 years running of Hyper-Kamiokande (10 years running of SK). Second, I review the method which I call the BNL strategy, in which one tries to explore CP violation through observing oscillatory pattern of neutrino oscillation. Motivated by the approval of the JPARC neutrino program, I also discuss a low-energy realization of the BNL strategy. It is meant to measure neutrino oscillation at the first and the second oscillation maxima by two HKs placed at Kamioka and somewhere in Korea. It is suggested by very rough argument that 8 years running in ν and $\bar{\nu}$ modes with one HK at Kamioka is equivalent to 2 years running in ν mode with two HK complex.

1. Introduction

Under the title kindly given to me by Milla, to whom we all would like to thank for her enthusiasm of having the workshop in such a place of scenic beauty, Venice, I will try to describe some new as well as the old ways of detecting CP violation. Exploring leptonic CP violation is the right topics in the workshop in this location; we should remember, in trying to discover CP violation, the courage possesed by Marco Polo who was brave enough to go on voyage to unexplored world and even have reached close to a far distant country Japan!

I think it timely to discuss ways of exploring leptonic CP violation at the end of 2003. About a year ago, the first result of KamLAND [1)] told us that the solution to the solar neutrino problem is given by the MSW large-mixing-angle (LMA) solution [2,3)]. It not only beautifully settled the problem which lasted nearly 40 years [4)] but also opened the door to our expedition to a CP violating world. Now, the two solar neutrino experiments, SNO and Super-Kamiokande (SK), both state that the larger Δm^2_{12} LMA-II region is excluded at 99 % CL in the analysis with 2 degrees of freedom [5,6)]. By combining them the statistical significance of the statement is now 99.9 %

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CL [7]. Therefore, we have finally pinned down the unique parameter region in the (1-2) sector of lepton flavor mixing, LMA-I. Together with the pioneering discovery of neutrino oscillation in the atmospheric neutrino observation by Super-Kamiokande [8], which is followed by the confirmation by K2K [9], we now know the structure of lepton flavor mixing in the (1-2) and (2-3) sectors of the MNS matrix [10]. Thus, we are left with the determination of the structure of its (1-3) sector, θ_{13} and CP violating phase δ.

First, I would like to mention the physics motivations for detecting leptonic CP violation. Why do we want to know about leptonic CP violation? My strongest motivation comes from better understanding of the concept of lepton-quark correspondence. Nowadays we all know from quantum anomaly consideration of the standard model that quarks and leptons are related with each other in a deeper level; we cannot remove any one of them without ruining the theory. We should remember, however, that our prejudice based on the experience in the quark sector badly failed in the lepton sector in which the large mixing angles are quite a commonplace event. I think it important to confirm (or refute) our prejudice that the leptonic Kobayashi-Maskawa phase is unsuppressed. It is truly remarkable that the importance of the concept of lepton-quark correspondence was recognized early in sixties by Shoichi Sakata and coworkers. They developed the Nagoya model, the neutrino-based unified model of quarks and leptons [11].

Another strong motivation comes from leptogenesis [12], the best candidate mechanism to date for generating baryon number asymmetry in the universe. Although there is no direct connection between the leptonic Kobayashi-Maskawa phase δ and the phases which are responsible for leptogenesis at high-energies, it is conceivable that the low-energy phase δ contains certain combinations of the effect of high-energy CP violating phases. For more about this possibility, see Pascoli's talk [13] in this workshop.

2. Comparing Neutrino and Antineutrino Appearance Experiments; Good-Old Way of Measuring CP Violation

2.1. A Brief History

Let me start by describing the story in good-old days of detecting leptonic CP violation. Though it is not the main concern in my talk, let me mention about it briefly because it is the right time to recollect the past and foresee the future. (I must, however, warn the readers that nothing is new in this section.) To the best of my knowledge, it was first noted by Cabibbo [14] that leptonic CP violation can be detected by observing the difference between neutrino oscillation probabilities

$P \equiv P(\nu_\mu \to \nu_e)$ and $\bar{P} \equiv P(\bar{\nu}_\mu \to \bar{\nu}_e)$. In vacuum, it takes the form

$$P - \bar{P} \equiv P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = -4J \left(\frac{\Delta m^2_{12} L}{4E} \right) \sin^2 \left(\frac{\Delta m^2_{13} L}{4E} \right), \tag{1}$$

under the approximation that $\frac{\Delta m^2_{12}}{\Delta m^2_{13}}$ is small, where J stands for the Jarlskog factor $J = c_{12} s_{12} c_{23} s_{23} c^2_{13} s_{13} \sin \delta$. Despite the pioneering work done in seventies, we needed long time to start discussing seriously how to detect CP violation in an experimentally realistic setting. It is partly because we did not expect that the Jarlskog factor which controls the order of magnitude of the CP violating effect can be as large as $J/\sin \delta \simeq 0.04$ (assuming the saturation of the CHOOZ bound [15]) as we know today.

The modern revival of interests in observing leptonic CP violation was triggered by works done in 1996-97 by Arafune *et al.* and others [16,17,18,19]. It was then followed by spurts of works on varying subjects which are too many to quote in this report. For more complete references including the ones in early era, see e.g., Refs. [18,33]. The topics included the issue of earth matter effect which might obscure the effect of CP violating phase, and where is the region of large CP violating effects.

People gradually recognized that there are two options, the low- and the high-energy options, to detect CP violation and measure δ. (For this classification, see [20].) The low-energy option [21,22,23] is advantageous because effect of CP violation is large at low energies. It is practically the unique option for conventional superbeam type experiments whose idea may be traced back to [23,24]. It is nice to see that the idea of low-energy superbeam has concrete realization as feasible experimental programs; Refs. [25], [26], and [27] from low to high energies.

On the other hand, the high-energy option was very popular among people despite that CP violating effects are small. People coined into the high-energy option because they favored the idea of neutrino factory [28,29,30] which utilizes intense neutrino flux from muon storage ring, whose flux is (supposed to be) so high as to easily overcome the smallness of the effects. The advantage of using high energy beam in neutrino factory comes from the features that beam convergence and cross sections are larger while the background is lower. (See Ref.[31] and Ref.[32] for most complete sensitivity analyses in which detailed experimental conditions and full correlations of errors are taken into account, respectively.)

The question of low- vs. high-energy options has not been settled yet. I personally believe that the low-energy option is the correct strategy to explore leptonic CP violation, and certainly it is the unique choice for tomorrow. But the ultimate answer to the question of which option is more profitable depends upon the size of θ_{13} and remains to be seen.

2.2. Displaying CP and Matter Effects in Terms of Bi-Probability Plot

So far so many words on "history". Let us now return to physics. Measuring

CP violation effect by observing $P - \bar{P}$ suffers from the problem of matter effect contamination. Fortunately, the matter effect is not overwhelming but is comparable with genuine CP violation due to the leptonic Kobayashi-Maskawa phase in relatively short (among LBL) baseline experiments such as the JPARC-SK project [26]. Then, it would be nice if we have a tool for representing these competing effects in a transparent way. In fact there exists a such tool called the "bi-probability plot" which was introduced in [33].

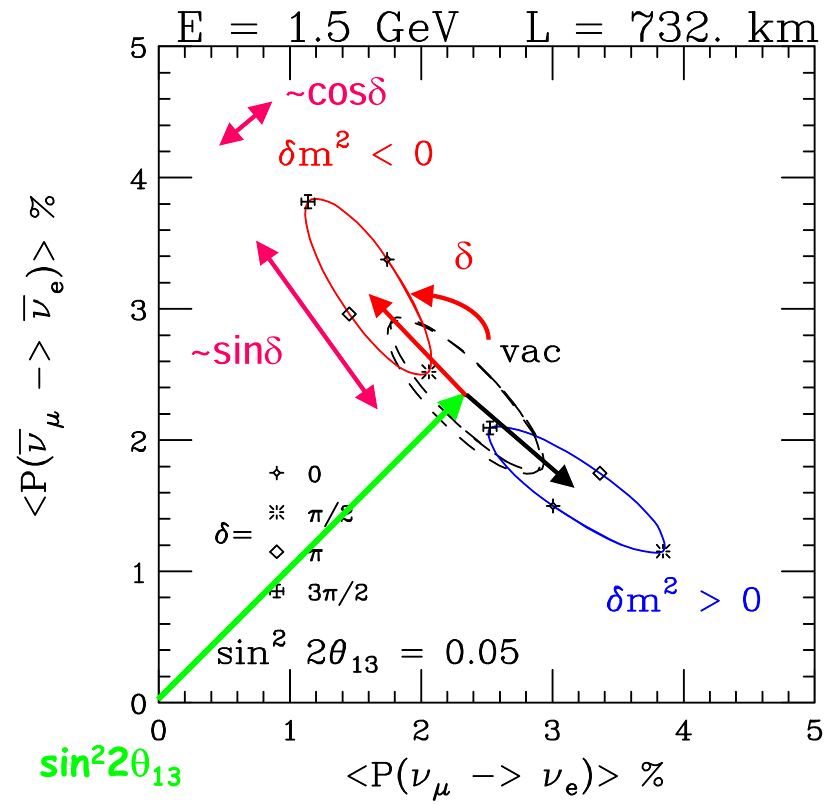

Figure 1: A P- $\bar{P}$ bi-probability plot with experimental parameters corresponding to NuMI off-axis project is presented for the purpose of exhibiting characteristic features of the neutrino oscillations relevant for low-energy superbeam experiments. Namely, it can disply competing three effects, CP violating and CP conserving effects due to δ as well as the matter effects in a compact fashion. For more detailed description of its properties, see [33].

In Fig: 1 we present a typical example which was kindly prepared by Adam Para using relevant parameters in NuMI off-axis project for his presentation somewhere. One can observe from Fig. 1 that the three effects, the CP violating and CP conserving effects due to δ as well as the matter effect, are represented in a compact way in a single diagram. By giving two observable P and $\bar{P}$, you can draw a dot in $P - \bar{P}$ space, and it becomes a closed ellipse when δ is varied.

As indicated in Fig: 1 the lengths of major and minor axes (the "polar" and "radial" thickness of the ellipses) represent the size of the $\sin\delta$ and the $\cos\delta$ terms,

respectively, whereas the distance between two ellipses with positive and negative Δm^2_{13} displays the size of the matter effect. Finally, the distance to the center of the ellipse from the origin is essentially given by $\sin^2 2\theta_{13}$. Notice that all the features of the bi-probability plot except for distance between $\Delta m^2_{13} = \pm$ ellipses are essentially determined by the vacuum parameters in setting of E and L relevant for the superbeam experiments. Therefore, one can easily guess how it looks like in the other experimental settings. As indicted in Fig: 1, the CP violating and CP conserving effect of δ are comparable in size with the matter effect.

Utility of the bi-probability plot is not just limited to the $P - \bar{P}$ plot as in Fig: 1, and it has wider applications. It was used to make features of comparison of different two experiments and/or measurement more transparent [34]. We will see more examples of applications in the following sections.

2.3. $P - \bar{P}$; CP or Matter Effects?

Now, I just want to make a clarifying remark. It is often claimed that one can determine the sign of Δm^2_{13} by measuring $P - \bar{P}$. On the other hand, I have said that $P - \bar{P}$ tells you the effect of CP violation. How these two facts are made consistent with each other?

Let me answer the question. I first note that

$$\begin{aligned} P(\bar{\nu}_\mu \to \bar{\nu}_e; \Delta m^2_{13}, \delta, a) &= P(\nu_\mu \to \nu_e; \Delta m^2_{13}, -\delta, -a) \\ &\simeq P(\nu_\mu \to \nu_e; -\Delta m^2_{13}, \pi + \delta, a), \end{aligned} \tag{2}$$

where $a = \sqrt{2} G_F N_e$ is the famous index of refraction of Wolfenstein [2]. The last equality approximately holds [35] due to the fact that $\Delta m^2_{12} \ll \Delta m^2_{13}$. Then, $\Delta P \equiv P - \bar{P}$ can be written as

$$\begin{aligned} \Delta P &\equiv P(\nu_\mu \to \nu_e; \Delta m^2_{13}, \delta, a) - P(\bar{\nu}_\mu \to \bar{\nu}_e; \Delta m^2_{13}, \delta, a) \\ &\simeq P(\nu_\mu \to \nu_e; \Delta m^2_{13}, \delta, a) - P(\nu_\mu \to \nu_e; -\Delta m^2_{13}, \pi + \delta, a). \end{aligned} \tag{3}$$

From (3) we can observe the following:

(1) If a measurement is done under the environment that dependence on CP phase δ is not sizable (which is not difficult to achieve because the effect is small anyway), then ΔP tells you the sign of Δm^2_{13}. If ΔP is positive, the sign of Δm^2_{13} is positive and vice versa.

(2) To detect leptonic CP violation as cleanly as possible, it is better to go to the region with less matter effect. This is the strategy exploited by the low-energy option for measuring CP violation [23].

2.4. T Violation; Cleanest Way of Detecting Genuine CP Violating Effect

Let me mention very briefly that measurement of T Violation is the cleanest

way of detecting genuine CP violating effect, though it is not easy to carry it out experimentally. It is because the oscillation probability can be written on very general ground as [36]

$$P(\nu_\alpha \to \nu_\beta) = A\cos\delta + B\sin\delta + C \tag{4}$$

where A, B, and C are functions of Δm^2_{13} and a. Then, the T violating measure ΔP_T is given by

$$\begin{aligned}\Delta P_T &\equiv P(\nu_\alpha \to \nu_\beta; \Delta m^2_{13}, \delta, a) - P(\nu_\beta \to \nu_\alpha; \Delta m^2_{13}, \delta, a) \\ &= 2B\sin\delta \end{aligned} \tag{5}$$

for symmetric matter profile. It stems from the fact that only the coefficient B is antisymmetric under the interchange $\alpha \leftrightarrow \beta$. Therefore, if $\Delta P_T \neq 0$, then $\delta \neq 0$ even in matter. The matter effect cannot create fake T violation. (Note, however, that the matter effect modifies the coefficient B in Eq. (5), whose feature is made transparent in [37].)

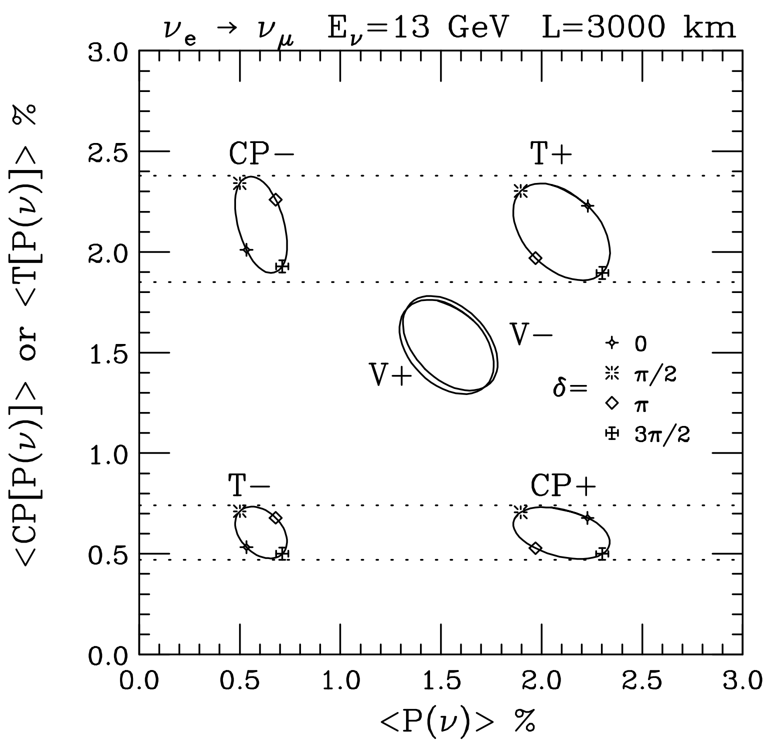

Figure 2: A simultaneous P- $T[P]$ and P- $\bar{P}$ bi-probability plot with experimental parameters corresponding to (nearly) optimal energy and baseline of maximal exhancement of T violating effect [37]. Notice the difference between movement of the direction in P- $T[P]$ and P- $\bar{P}$ plot; they are orthogonal with each other for reasons explained in the text.

Again the feature of T violating measure ΔP_T can be clearly represented by the similar bi-probability plot [35]. As shown in Fig: 2 the matter effect splits positive

and negative Δm^2_{13} ellipses but along the diagonal in the $P-T[P]$ plot. It is because the point of $\delta = 0$ on ellipses must remain on the diagonal line, as dictated by (5). On the other hand, the movement of the two ellipses are along orthogonal ("polar") direction in the $P-CP[P]$ bi-probability plot as exhibited in Fig: 2. A secret behind the structure of "baseball diamond" in the simultaneous $P-T[P]$ and $P-CP[P]$ bi-probability plot (Fig:2) is explained in [35].

To carry out the T violation measurement, we must wait for the construction of an intense electron (anti-) neutrino beam either by beta beam [38] or neutrino factory.

3. New Ways of Measuring CP Violation

We now address the original topics of this talk, new ways of detecting CP violation. We discuss two approaches. The first one is by combining LBL measurement with reactor experiment, a possibility raised quite recently [39]. The second one is the strategy pursuit by people in Brookhaven National Laboratory [40]. Let me call the latter, the BNL strategy.

3.1. Reactor-LBL Combined Method

We start with the reactor-LBL combined method. The reasoning behind the proposal is as follows. In conventional way of detecting CP violation by LBL experiments one has to measure appearance probability not only in neutrino channel but also in antineutrino channel. But, there are greater difficulties in the antineutrino appearance measurement compared with that in the neutrino mode. They include a factor of 3 smaller reaction cross sections and severer background, even ignoring the issue of slightly less intense $\bar{\nu_\mu}$ beam. The former implies that 3 times longer running time is required for accumulation of equal number of events with that in neutrino channel.

Therefore, it would be nice if there exists another way of complementing neutrino mode appearance measurement in LBL experiments. A natural possibility is the reactor experiment for θ_{13} as a pure measurement of this angle independent of other mixing parameters [41].

The principle of detection of CP violation by the reactor-LBL combined method is in fact very simple. LBL ν_e appearance experiment will observe the neutrino oscillation probability $P(\nu_\mu \to \nu_e)$. In leading order in $\Delta m^2_{21}/\Delta m^2_{31}$ and s^2_{13}, it takes the form [31]

$$P(\nu_\mu \to \nu_e) \equiv P(\nu)_\pm = X_\pm s^2_{13} + Y_\pm s_{13} \cos\left(\delta \pm \frac{\Delta_{31}}{2}\right) + P_\odot, \qquad (6)$$

where $\pm$ refers to the sign of Δm^2_{31}. The coefficients $X_\pm$, $Y_\pm$, and $P_\odot$ are given by

$$X_\pm = 4 s^2_{23} \left(\frac{\Delta_{31}}{B_\mp}\right)^2 \sin^2\left(\frac{B_\mp}{2}\right), \qquad (7)$$

$$Y_{\pm} = \pm 8 c_{12} s_{12} c_{23} s_{23} \left(\frac{\Delta_{21}}{aL} \right) \left(\frac{\Delta_{31}}{B_{\mp}} \right) \sin \left(\frac{aL}{2} \right) \sin \left(\frac{B_{\mp}}{2} \right), \tag{8}$$

$$P_{\odot} = c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{21}}{aL} \right)^2 \sin^2 \left(\frac{aL}{2} \right) \tag{9}$$

with

$$\Delta_{ij} \equiv \frac{|\Delta m_{ij}^2| L}{2E} \quad \text{and} \quad B_{\pm} \equiv \Delta_{31} \pm aL, \tag{10}$$

where $a = \sqrt{2} G_F N_e$ denotes the index of refraction in matter with G_F being the Fermi constant and N_e a constant electron number density in the earth. We use in this paper the standard notation of the MNS matrix. The mass squared difference of neutrinos is defined as $\Delta m_{ji}^2 \equiv m_j^2 - m_i^2$ where m_i is the mass of the i-th eigenstate.

Let me simplify the discussion by taking the energy corresponding the first oscillation maximum $\Delta_{13} = \pi$. In fact, there exist a number of reasons for tuning the beam energy to the oscillation maximum in doing the appearance and the disappearance measurement in LBL experiments, as listed in [42]. In this case, $\cos\left(\delta \pm \frac{\Delta_{13}}{2}\right) = \mp \sin\delta$ and (6) can be solved for $\sin\delta$ as

$$\sin\delta = \frac{P(\nu) - P_{\odot} - X_{\pm} s_{13}^2}{\mp Y_{\pm} s_{13}}. \tag{11}$$

We note that, since θ_{13} can be measured by reactor experiments, the right-hand side (RHS) of (11) consists solely of experimentally measurable quantities. Therefore, LBL measurement of $P(\nu_\mu \to \nu_e)$, when combined with the reactor experiment, implies measurement of $\sin\delta$. One can easily show that the argument can be generalized to the case off the oscillation maximum.

The real question is, however, if it is really possible to carry out such reactor-LBL combined measurement of CP violation in a realistic setting. If yes, the next question is what would be the required conditions for the reactor and the LBL experiments for the purpose. To answer the questions we have performed a detailed statistical analysis assuming reasonable systematic errors. For LBL experiment, we take the neutrino-mode appearance measurement in the JPARC-HK(SK) experiment which includes the effect of background after severe cut for π^0 rejection. For reactor θ_{13} experiment, we assume the systematic errors which are likely to be achieved based on our estimation [41] in designing the reactor experiment at the cite of Kashiwazaki-Kariwa nuclear power plant.

We take the following procedure in our analysis. We pick up a point in the two-dimensional parameter space spanned by δ^{best} and $\sin^2 2\theta_{13}^{best}$ and make the hypothesis test on whether the point is consistent with CP conservation within 90% CL. For this purpose, we use the projected $\Delta\chi^2$ onto one-dimensional δ space [39]. Then, a collection of points in the parameter space which are consistent with CP conservation

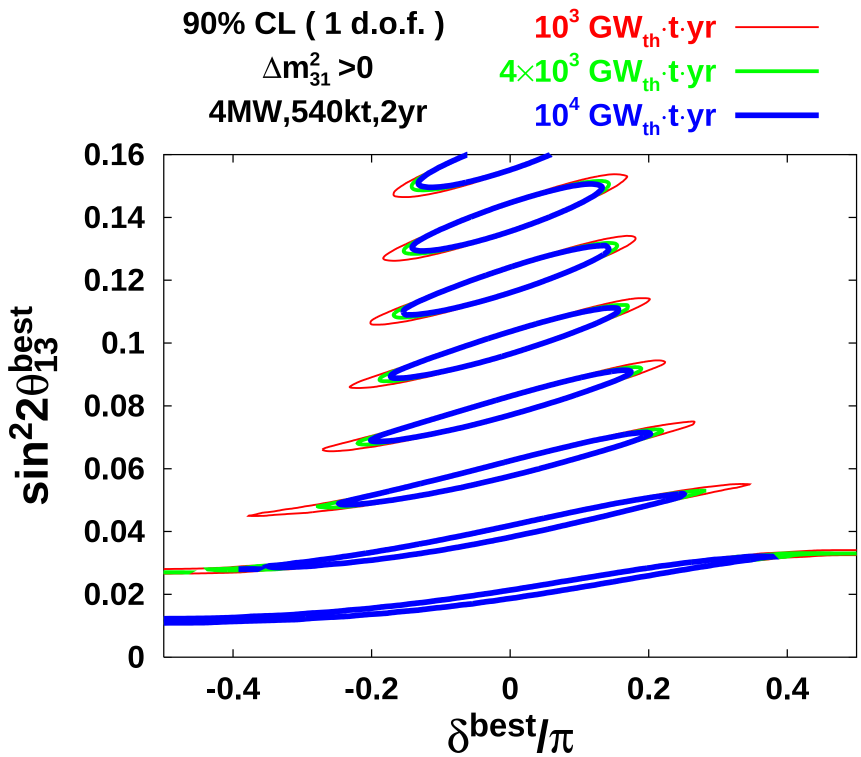

Figure 3: The contours are plotted for eight assumed values of $\sin^2 2\theta_{13}$ which range from 0.02 to 0.16 to indicate the regions consistent with the hypothesis $\delta = 0$ at 90% CL by the reactor-LBL combined measurement. If an experimental best fit point falls into outside the envelope of those regions, it gives an evidence for leptonic CP violation at 90% CL. The thin-solid (red), solid (green), and thick-solid (blue) lines are for 10^3, 4×10^3, and 10^4 GW$_{th}$·ton·year exposure of a reactor experiment, respectively, corresponding to about 0.5, 2, and 5 years exposure of 100 ton detectors at the Kashiwazaki-Kariwa nuclear power plant. For the JPARC-HK experiment, 2 years measurement with off-axis 2° ν_μ beam is assumed. The normal mass hierarchy, $\Delta m^2_{13} > 0$, is assumed.

form a region surrounded by a contour in δ^{best}-$\sin^2 2\theta_{13}^{best}$ space, as will be shown in Figs: 3 and 4. Or conversely, if an experimental best fit point falls into outside the envelope of those regions, it gives an indication for leptonic CP violation because it is inconsistent with the hypothesis $\delta = 0$ at 90 % CL. We take the neutrino mixing parameters which correspond to the LMA-I solar neutrino solution.

In Fig: 3, we present the results of the CP sensitivity analyses by assuming neutrino-mode appearance measurement at JPARC-HK for 2 years and reactor measurement of $10^3 - 10^4$ GW$_{th}$·ton·year. The fiducial volume of HK is taken as 540 kton and the upgraded beam power of 4 MW is assumed. In Fig: 4, we give the results of similar analysis by using 10 years running of SK with fiducial volume 22.5 kton and beam power 0.75 MW. We observe from Fig: 3 that there is a chance for reactor-LBL combined experiment of seeing an indication of CP violation for relatively large θ_{13}^{best},

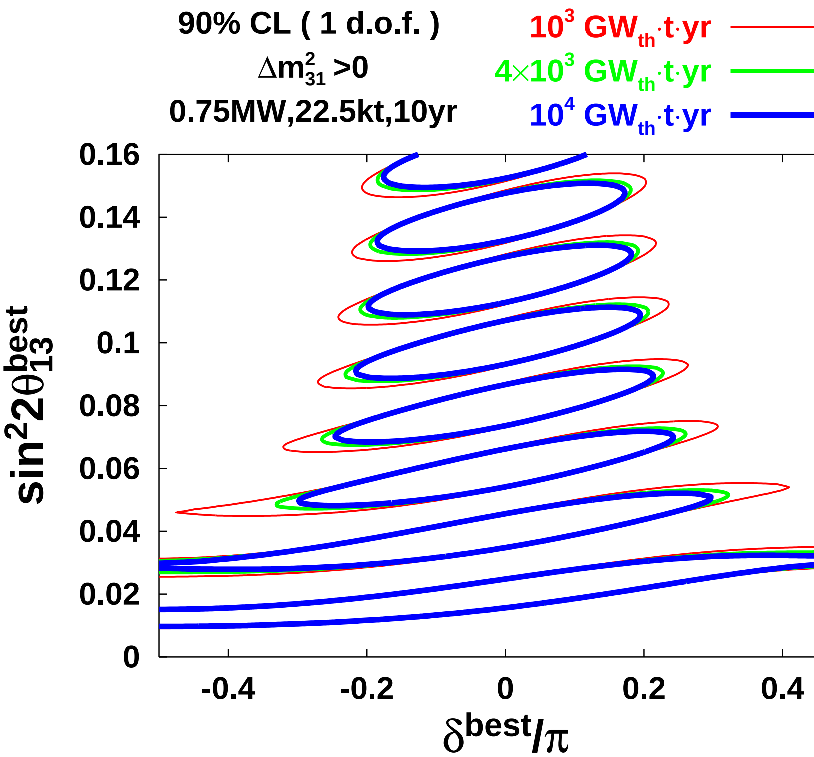

Figure 4: The same as in Fig: 3 but with 10 years running of JPARC-SK experiment with the fiducial volume of 2.25 kton and the beam power of 0.75 MW.

$\sin^2 2\theta_{13}^{best} \geq 0.03$ at 90 % CL. Moreover, it is truely remarkable that the sensitivity to CP violation is not lost and remains for $\sin^2 2\theta_{13}^{best} \geq 0.04$ with SK, though data taking by SK for 10 years may be painful. Without HK, the reactor-SK combined measurement might be the unique way of detecting leptonic CP violation.

The sign of Δm^2_{13} is taken to be positive in Figs: 3 and 4, which corresponds to the normal mass hierarchy. If we flip the sign of Δm^2_{31} (the case of inverted mass hierarchy) we obtain almost identical CP sensitivity contours. Then, it looks like that the sign of Δm^2_{13} does not produce any serious problems. Unfortunately, it is not true. If we do not know the sign, there arises a severe limitation on our ability of detecting CP violation by the reactor-LBL combined method. In this case, one has to allow the possibility that we take a wrong sign in analyzing the reactor-LBL combined measurement. Then, one can show that about half of the sensitivity region is lost [39)]. This is nothing but the problem of parameter degeneracy due to unknown sign of Δm^2_{13}, the two-fold ambiguity first noticed in [33)]. Therefore, determination of the sign of Δm^2_{13} must be done prior to the reactor-LBL combined measurement of CP violation. This is a part (only a part) of the reasons why I enphasized the importance of measuring the sign of Δm^2_{13} in my contribution in the panel discussion

[43]. See Ref. [39] for details of the treatment of background and the complexity which arises due to the unknown sign.

3.2. BNL Strategy; A Brief Review

An interesting new idea was developed by people in Brookhaven National Laboratory which is described in [40]. Let me briefly review it. The basic idea is as follows. As I described earlier, the conventional way of detecting CP violation is to compare $P(\nu_\mu \to \nu_e)$ with $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ at around the first oscillation maximum, $\frac{\Delta m^2_{13} L}{4E} = \frac{\pi}{2}$. Instead of following the canonical path, one can think of a new possibility that if one could observe a full neutrino oscillation pattern the effect of δ should manifest itself. To incorporate this idea into the experiment it must be able to see not only the first but also the second and the third oscillation maxima. Then, one need to use high energy beam and longer baseline so that the oscillatory pattern is not to be buried into the Fermi motion. See Fig. 3 of the first reference in [40]. The design proposed by BNL group employs the wide-band beam from upgraded AGS to 1 MW whose energy specrum extend to $\sim$ 6 GeV with baseline distance of 2540 km. The beam spread covers the first, the second and the third oscillation maxima which are located at about 5, 1.6, and 1 GeV, respectively.

The strategy and the resultant proposal seem to deserve closer attention assuming that severer background issue in water Cherenkov detector at higher energies is overcome. The group did a detailed simulations and estimated the sensitivities of various observables. So you can judge by yourself by looking into [40]. Yet, let me make a few remarks, some good ones first and then a sour one next. Good ones are that there is a number of favorable features in the BNL strategy. Of course, it is nice to explore the neutrino oscillation pattern which has never been done in a clear way.[b] Despite the usage of a baseline longer than 2000 km its sensitivity goes down to rather small value of θ_{13}, $\sin^2 2\theta_{13} \simeq 0.005 - 0.04$ at 90 % CL depending upon δ and the sign of Δm^2_{13}. In fact, the long baseline is advantagious for smaller values of Δm^2_{13}, and its sensitivity may extends even to the solar Δm^2_{12}.

My sour comment is on the sensitivity of detecting CP violation to be achieved by the concrete design of the experiment proposed by the BNL group. As indicated in Fig. 10 in the second reference in [40], the sensitivity of δ determination is limited to 20-30 degree at 1σ CL for $\sin^2 2\theta_{13} = 0.04$. It may be compared with the similar accuracy claimed by the JPARC-HyperKamiokande group but at 3σ CL [26]. I want to note that it is not completely fair to compare the sensitivities claimed by the both groups in an equal footing. LOI of the JPARC-HK experiment assumes 4 MW as

[b] An evidence for a dip at the first oscillation maximum in the ratio of data to Monte Carlo prediction in atmospheric neutrino observation has recently been reported by the Supar-Kamiokande group [44], the first clear demonstration of the oscillatory behavior. This is the comment inserted to this article in the last minute but I feel I should do it because it is so important.

the beam power, whereas BNL proposal takes 1 MW. But even after taking account of the difference in beam intensity, it appears to me that the much less sensitivity in CP detection in the BNL proposal arises because of limited statistics due to long baseline distance, which results in a factor of $\sim$ 100 less beam intensity than that of JPARC-HK per MW.[c]

Of course, it is not quite meaningful to compare the sensitivities of the two experiments which employs different detection principles and differs in background and detector systematics. The real question is if there are ways to improve the sensitivity along the line of the BNL strategy. I emphasize that if my prejudice that the statistics is of key issue in CP measurement is right, an L/E scaled realization of the BNL strategy by using the NuMI beam at Fermilab is worth to consider.

3.3. A Low-Energy Realization of BNL Strategy

Let me now address the last topics of this talk, a possible low-energy realization of the BNL strategy. My motivation is as follows: the JPARC-SK program is now funded. (It was not quite decided at the time of the workshop, but it was likely as I indicated in my contribution at the panel discussion.) Therefore, we will definitely have a neutrino superbeam in Japan in 2008 or so. Then, the natural question is "are there any possibilities of realizing the BNL strategy by utilizing the beam?".

We cannot think of high energy beam, like the one in the BNL proposal, in the JPARC project, because the JPARC neutrino beam is an off-axis beam which will be tuned to $\sim$ 600 MeV, the first oscillation maximum at SK. With baseline distance of 300 km the second and the third maxima are buried into the Fermi motion anyway. Therefore, the only possibility we can think of is the second detector specialized to measure neutrino oscillation at around the second oscillation maximum.[d] Clearly, we need three-times longer distance to have $\frac{\Delta m^2_{13} L}{4E} = \frac{3\pi}{2}$. It requires $L \simeq 900$ km from JPARC in Tokai village toward the direction to Kamioka; Korea! [e]

Let us examine the hypothetical experiment with one Hyper-Kamiokande (HK)

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[c]This interpretation might be too naive if the claim that the sensitivity is approximately L-independent up to $\sim$ 4000 km [45] is true.

[d]This is different but reminiscent of the two detector proposal [19] in its basic idea of detecting CP violation by observing neutrino oscillation at two different values of relative phase between two flavor states.

[e]I am aware that the distance between Tokyo and Seoul is longer than 900 km. It is more like 1100 km. Then, a question arises as to if our strategy of measurement at the first-second oscillation maxima works. My answer is as follows. Suppose that $\Delta m^2_{13} = 2 \times 10^{-3}$ eV^2 as suggested by the most recent atmospheric neutrino analysis by SK group [46]. Then, it may not be optimal to tune the beam energy to the first oscillation maximum at Kamioka because it is as low as 480 MeV. It is quite conceivable to run at slightly higher energy and let me take it to 600 MeV. In this case, $\Delta_{13}^{Kamioka} = 0.8\pi$, slightly below the first oscillation maximum. Then, $\Delta_{13}^{Korea} = 1.03 \times 3\pi$, which is almost the second oscillation maximum. If $\Delta m^2_{13} = 2.5 \times 10^{-3}$ eV^2, $\Delta_{13}^{Kamioka} = \pi$ and $\Delta_{13}^{Korea} = 1.2 \times 3\pi$, $\sim$ 20 % higher than the second oscillation maximum.

in Kamioka and the second HK in somewhere in Korea, a bit more expensive one compared with the current JPARC-HK project! We shoot neutrino superbeam from JPARC, I mean no antineutrino beam for this consideration, and detect them by the two HKs.

To reveal the qualitative features of the experiment I draw the bi-probability plot appropriate for the setting. The result is given in Fig: 5 in which the abscissa is taken to be the appearance probability $P = P(\nu_\mu \rightarrow \nu_e)$ in Kamioka, and the ordinate is the appearance probability P in Korea. The beam energy is assumed to be tuned to 600 MeV which is close to the first oscillation maximum at Kamioka for $\Delta m^2_{13} = 2.5\times10^{-3}$ eV^2, and the monochromatic beam is assumed as a first approximation.

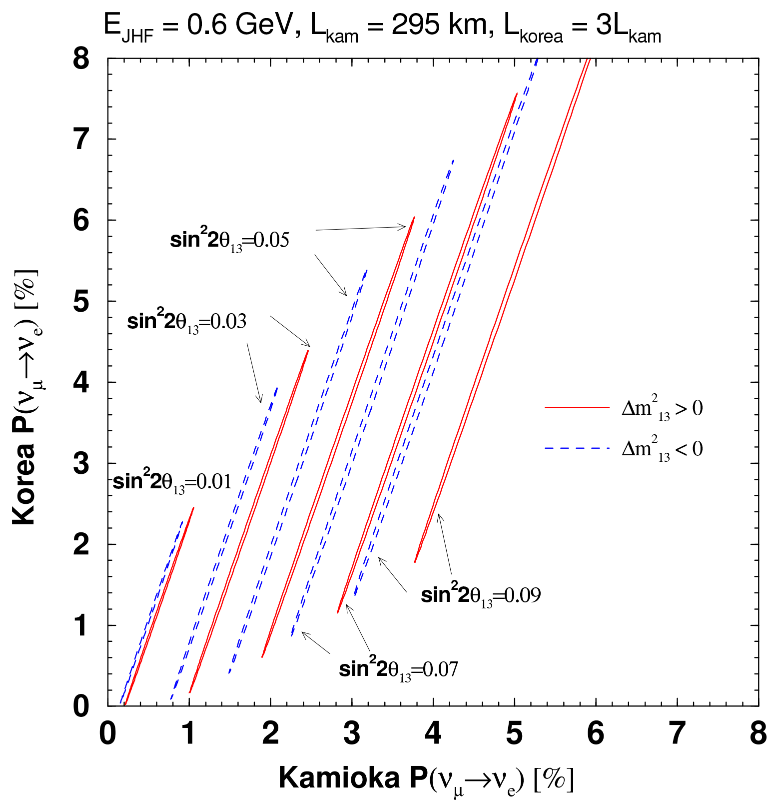

Figure 5: A Kamioka-Korea bi-probability plot is presented with neutrino beam energy 600 MeV and the baseline lengths $L_{Kamioka} = 295$ km and $L_{Korea} = 3L_{Kamioka}$. The neutrino mixing parameters are taken as follows: $\Delta m^2_{13} = 2.5 \times 10^{-3}$ eV^2 and $\theta_{23} = \pi/4$. The LMA-I solar mixing parameters are taken as in [34].

A distinctive feature of the plot is that the slope of the shrunk ellipse is about -3 in contrast to the slope which is close to -1 in the $P - \bar{P}$ plot. (See, e.g., [42].) It can be easily understood as a consequence of the combined measurement at the first and the second oscillation maxima. To understand this point I use the expression of oscillation probability given in (6). One can easily show for given two measurement

P_1 in Kamioka and P_2 in Korea

$$P_2 = -\frac{Y_2}{Y_1} P_1 + \frac{1}{Y_1} \left(X_1 Y_2 - X_2 Y_1 \right) s_{13}^2 \tag{12}$$

where $\pm$ index for the sign of Δm_{13}^2 is suppressed. Under vacuum oscillation approximation in (8), which should be a reasonable approximation in this setting, the slope of the shrunk ellipse can be estimated to be

$$\frac{Y_2}{Y_1} \simeq \frac{L_2}{L_1} = 3 \tag{13}$$

reflecting the ratio of the baseline distances corresponding to the first and the second oscillation maxima.

What does the steeper slope in the Kamioka-Korea bi-probability plot mean? It means that if the statistical error is comparable (assuming the systematic error is the same), the Korean detector is more important in determination of CP phase δ. It is because the size of the ellipse is due to variation of δ and therefore the extension of the ellipse along the Korean axis implies the larger sensitivity for measuring δ. Of course, the situation is not easy to realize, because we need to have 10 megaton HK in Korea to equalize numbers of events in both HK. So let me restrict myself into more "conservative" assumption of two identical HK in Kamioka and Korea. Then, the statistical error in Korean HK is worse by a factor of 3 and it exactly cancels the factor of 3 merit of the extended ellipse.

Thus, it looks like that the merit of Korean detector for measurment of δ is comparable with antineutrino measurement by HK in Kamioka. This is, of course, not quite true because one need 3 more years in the antineutrino channel to have equal number of events with the neutrino channel. Furthermore, the Kamioka-Korea detector complex can operate simultaneously with neutrino beam for $\sim$ 10 years with less relative systematic errors. Therefore, 8 years running of ν and $\bar{\nu}$ modes with one HK at Kamioka, admittedly very roughly speaking, is equivalent to 2 years running of ν mode with the Kamioka-Korea two HK complex. Unfortunately, the difficulty in determining the sign of Δm_{13}^2 still remains with us in this new type of measurement, as indicated in Fig: 5.

I hope that I demonstrated the merit of possible Kamioka-Korean detector complex in the CP violation search. At the very least, it may serve for a better understanding of the secret of power of the BNL strategy. Moreover, I personally believe that this possibility is worth greater attention; if θ_{13} turns out to be smaller than the sensitivity limit of JPARC-SK search, then we might want to consider this possibility seriously. In this case, we should think about operating both ν_μ and $\bar{\nu}_\mu$ beams and optimization of relative time sharing is required. Of course, if one really thinks about the over-all merit of such project, one should also integrate various other capabilities including *in situ* determination of the sign of Δm_{13}^2.

I would like to mention here that the idea and interests for having underground detector in Korea has been described earlier [47]. I was delighted to learn during the workshop that the interest still continues to exist among people in Korea [48].

4. Concluding Remarks

I have discussed some new ideas of how to explore leptonic CP violation which might prove profitable in certain circumstances. The reactor-LBL combined method is useful to start exploring CP violation simultaneously with ν mode operation of LBL without waiting for its $\bar{\nu}$ mode operation. While its sensitivity is limited and may not exceed 2 σ CL, it can be the first indicator of CP violation if θ_{13} is relatively large, $\sin^2 2\theta_{13} > 0.05$ or so. Any informations about CP phase δ is certainly of help to optimize the operation of ν and $\bar{\nu}$ mode operation of LBL experiments. Moreover, it may be the only way to explore leptonic CP violation if HK is not built, a pessimistic scenario.

I also discussed extremely optimistic case of two HK complex, one at Kamioka and the second one in Korea. What is the real need for such an expensive option? Well, we do not know the size of θ_{13}, and the JPARC-SK experiment may fail to detect ν_e appearance, as cautiously remarked by Nishikawa [49] in his comments in the panel discussion. If it turns out to be the case, we need much higher sensitivity for CP violation search. The sensitivity would be greatly increased if there is the second HK which can explore the region around the second oscillation maximum, as I suggested in an admittedly very rough treatment. I hope that it is a practical way to overcome the limitation of the sensitivity in CP violation search by the current design of the JPARC-HK project. It may worth serious attention if the ν_e appearance signal at the phase-I of the JPARC-SK experiment is vague at the verge of its sensitivity.

In summary, I am under the strong feeling that the good-old strategy of detecting CP violation by measuring appearance probabilities P and $\bar{P}$ by low-energy super-beam experiments is still the most promising one. Yet, we may need some other ideas for cases of unexpected situation such as tiny θ_{13}, or financial difficulty which might prevent us from construction of larger detectors.

The final goal of exploring CP violation may be resolving the parameter degeneracy completely, the topics that I failed to cover in my presentation. In short, it is the problem of multiple solutions for a given set of observable of P and $\bar{P}$. It can be viewed as intrinsic degeneracy [50] in solution of a set of parameters (δ, θ_{13}), which is enriched by two kind of discrete degeneracies due to the sign of Δm^2_{13} [33] and the first-second octant ambiguity of θ_{23} [51]. See Ref. [52] for global overview and a list of the references. At the present status of our understanding of the notorious problem, we may need extreme facility such as neutrino factory to solve it completely [53]. It is nice to see that an important step toward realization of the ultimate option is put

forward in Europe [54].

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